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Production of Volume Wave Plasma with Internally Mounted Cylindrical Planar Microwave Launcher and Two-Dimensional Field Analysis Using Finite Difference Time Domain Method

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In this paper, we presented experimental results on the production of volume wave plasma (VWP) using an internally mounted cylindrical planar microwave launcher, for application to novel plasma processings, such as inner wall coating, impurity-free etching or internal sterilization of medical instruments using VWP. It was demonstrated that the ellipsoidal VWP is produced in front of a microwave launcher in He or Ar gas atmosphere. Numerical analyses of microwave fields radiated from a planar launcher have been carried out using the two-dimensional finite difference time domain (FDTD) method to determine the mechanism of VWP production in middle of the chamber. It was shown that the calculation results showed fairly good agreements with the experimental results measured using a dipole antenna probe. The spatial distributions of plasma density and the temperature of VWP were also measured using a double probe. It was found that the electron density is comparable to or slightly less than cutoff density of $7.4 \times 10^{10}\,\mathrm{cm}^{-3}$ corresponding to the microwave frequency of $f_m = 2.45$ GHz, and that the electron temperature is approximately 6 eV at the plasma center. [DOI: 10.1143/JJAP.44.L352]

KEYWORDS: microwave launcher, volume wave plasma, field analysis, FDTD

Large-area microwave plasmas have been widely used for various applications in the fabrication of electronic materials, such as ULSIs, solar cell films, and liquid crystal thin-film transistors. Recently, new functional materials, such as carbon nanotubes and nanocrystalline diamond films, have been extensively studied using microwave plasma aided chemical vapor deposition.

In general, planar-type overdense microwave plasmas produced without magnetic fields are called the surface wave plasma (SWP).[1–3] They have a number of advantages in producing high-density ($n_e > 10^{11}\,\mathrm{cm}^{-3}$), large-area ($L >$ 50 cm) plasmas at pressures ranging from a low pressure of ~mTorr to a moderate pressure of ~10 Torr.[4–6] In some applications, however, it is desired to produce the plasma just on the substrate located inside a vacuum chamber, to prevent contamination by impurities generated via the interaction between the plasma and wall materials, such as metal, aluminum and quartz. To satisfy such a requirement, we proposed here the production of volume wave plasma (VWP) in the mid space of the chamber, differently from plasma production using surface waves, in which plasma is usually produced just below the dielectric plate used as vacuum sealing. To produce VWP with microwaves at 2.45 GHz, we used a novel cylindrical planar launcher.[7] Numerical analysis of the field distributions of microwaves radiated from a planar cylindrical-type microwave launcher has been performed using a two-dimensional finite difference time domain (2-D FDTD) method. We also measured the spatial distributions of electric field intensity and plasma parameters in VWP using a double probe.

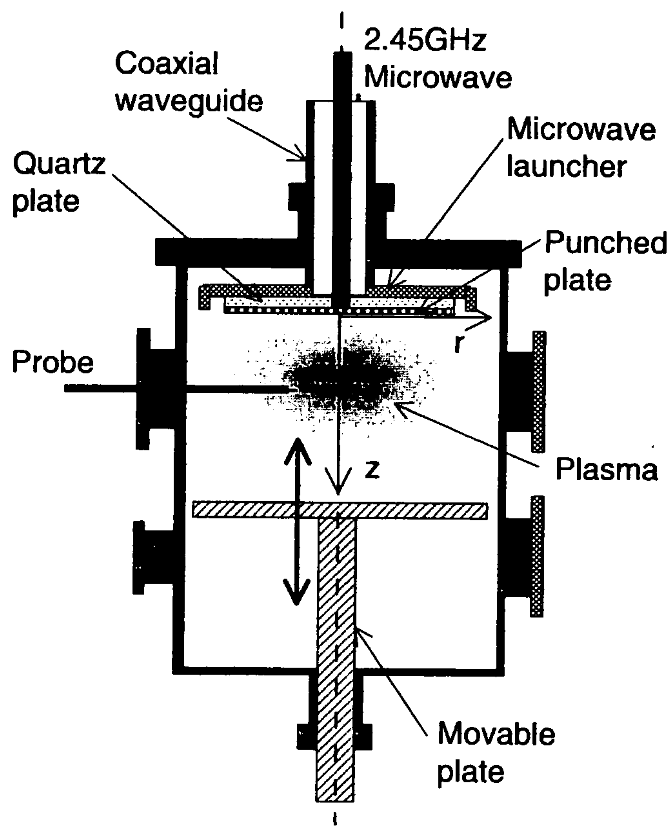

Fig. 1. Schematic drawing of experimental setup with planar microwave launcher.

The schematic drawing of the experimental setup for VWP production is shown in Fig. 1.[8] The inner diameter and height of the cylindrical vacuum chamber used are 250 and 500 mm, respectively. The chamber was pumped up to the order of mTorr by a rotary pump. The microwave launcher consisted of a coaxial waveguide and a planar cylindrical cavity, where a thin quartz plate was used for vacuum sealing. In the present launcher system, vacuum was sealed using an O-ring placed at the small area in the central part of the launcher, so that the thickness of the quartz plate could be reduced significantly. A circular quartz plate having a diameter of 220 mm and a thickness of 8 mm was used inside the planar microwave launcher. A stainless steel punched plate with a hole diameter of 8 mm was attached to

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the quartz plate, as shown in Fig. 1. A narrow gap of approximately 4 mm existed between the edge of the quartz disc and the surrounding metal frame of the microwave launcher. This narrow gap served as the microwave antenna in the VWP production. 2.45 GHz microwaves guided by a rectangular waveguide were transferred to the microwave launcher via a coaxial waveguide. The microwave power of the magnetron is variable from zero to 1.5 kW. After pumping the vacuum chamber, Ar or He gas was filled at a pressure of 0.1 to 1 Torr. By adjusting the position of the flat metal plate opposed with the microwave launcher, an ellipsoidal VWP discharge can be produced in the mid space in front of the launcher. To investigate field distributions inside the vacuum chamber, we measured electric field intensity using a movable dipole antenna. The tips of the probe were platinum wires of 0.2 mm diameter and 2 mm length, and the output of the probe was directly connected to the spectrum analyzer to measure the field distributions of 2.45 GHz microwaves. We also measured the electron density and temperature profiles of volume wave plasma using a double probe.

We produced VWP using the internally mounted microwave launchers shown in Fig. 1. VWP can be produced by adjusting the distance d between the movable facing metal plate and the microwave launcher. Figure 2 shows a photograph of Ar plasma discharge taken from the side port window under the following discharge conditions: $d = 203$ mm, gas pressure of 0.5 Torr, gas flow rate of 100 sccm and microwave power of 500 W. It is clear that ellipsoidal plasma was produced in front of the launcher. To investigate the plasma parameters of VWP, we measured electron density and temperature using the double-probe technique. Figure 3 shows the radial distributions of electron density and temperature measured using a double probe located at an axial distance from the quartz plate, $z = 65$ mm, where the incident microwave power was 500 W at a pressure of 0.1–0.3 Torr and $d = 203$ mm. It was found that electron temperature and density monotonically decrease with radial distance. The electron temperature at $r = 15$ mm was estimated to be approximately 5.4 eV. The maximum electron density obtained around the center of VWP was

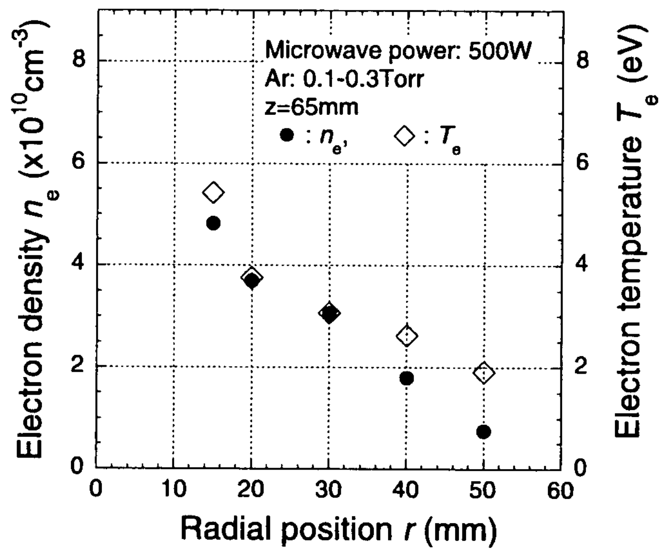

Fig. 3. Radial distributions of electron density and temperature at $z = 65$ mm.

comparable to or slightly lower than the cutoff density of 7.4×10^{10} cm^{-3} corresponding to a microwave frequency f_m of 2.45 GHz. Therefore, microwaves might penetrate inside the plasma, and form a certain cavity mode in the chamber.

It is interesting to note that VWP was repeatedly generated and disappeared in almost the same space in front of the microwave launcher when the opposite metal plate was scanned. The ellipsoidal VWP shown in Fig. 2 was produced with a good reproducibility at certain critical distances, such as $d = 135$, 203 and 275 mm. However, when the metal plate was moved by ± 10 mm from those positions, the plasma was deformed and finally disappeared. Hence, it is deduced from the present results that the production of VWP is strongly associated with the standing-wave structures of the microwave fields formed between the microwave launcher and the opposite metal plate. Figure 4 shows the field intensity of the axial field component measured using the probe fixed at $r = 0$ mm and $z = 65$ mm, while the opposite metal plate was scanned from $z = 110$ to

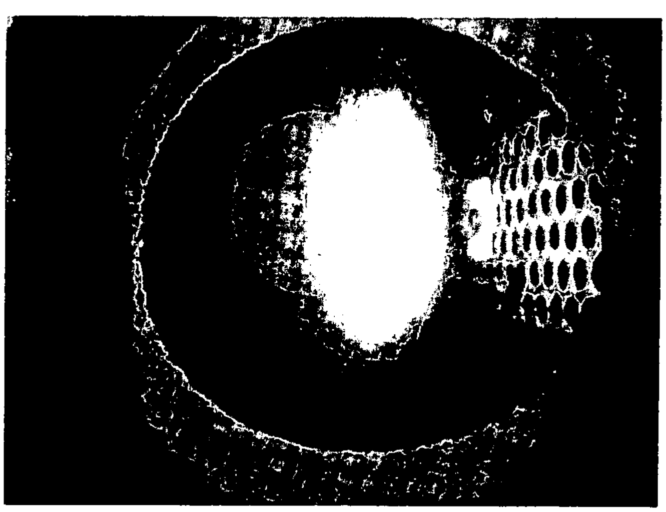

Fig. 2. Photograph of Ar plasma discharge taken from the side port window at gas pressure of 0.5 Torr and microwave power of 500 W.

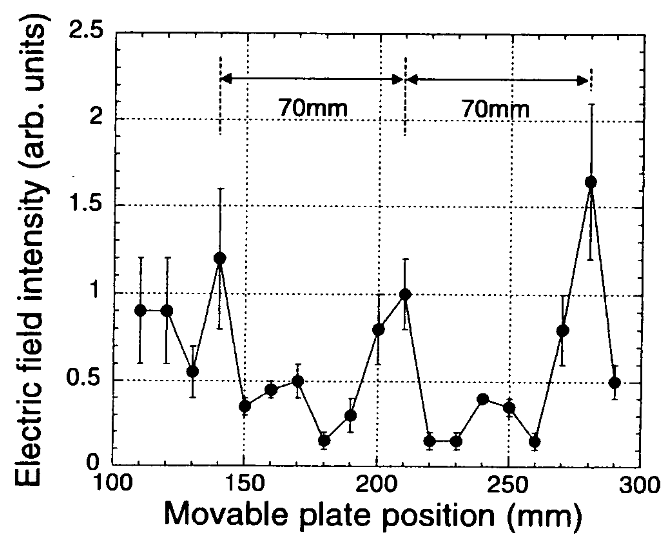

Fig. 4. Electric field intensity at $r = 0$ mm and $z = 65$ mm when the opposite metal plate was moved from 110 to 290 mm.

290 mm along the axial direction. It is clear that the spatial distribution of electric field intensity is that of the standing wave structure with an axial interval of approximately 70 mm. These results support the experimental finding that VWP can be repeatedly produced in a strong-field region by scanning the opposite metal plate.

We developed the 3-D FDTD calculation code for analyzing the field radiation pattern of the planar microwave launcher, which was improved from the 2-D FDTD code originally developed for the field analysis of microwave plasma devices for diamond film synthesis.[9] FDTD analysis is a numerical calculation method of solving Maxwell's equations by calculating centered difference approximation in both time and space domains, and then electromagnetic field intensity in the analysis space can be obtained.[10] In the numerical calculation, the time step Δt was taken as 0.4 ps which corresponds to 1/1000 of one period of microwave oscillation at 2.45G Hz, and the space steps Δr and Δz were taken as 2 mm to satisfy the convergence conditions of FDTD analysis. Since the present geometry was of axial symmetry, we used a simplified 2-D FDTD code. Furthermore, we simply regarded the punched metal plate as a flat planar plate having a diameter of 220 mm and a thickness of 2 mm, because the microwaves that leaked from the small holes are strongly damped as evanescent waves. Assuming that the plasma density was lower than the cutoff density, we carried out the FDTD analysis under the conditions without plasma in the discharge chamber. Figure 5 shows the calculation results of the spatial distributions of electric field intensity in the r-z plane. In this case, the microwaves propagate through the quartz plate of the launcher and form a certain cavity mode in the chamber. It should be noted that the electric field intensity has a strong peak at approximately $z = 70$ mm. The peak electric field is evaluated to be 39 kV/m, when the microwave power is 500 W and the movable metal plate position is at $z = 200$ mm. According to the empirical experimental data of microwave discharge,[11] this field strength of microwaves can sufficiently produce Ar plasma discharge at a pressure of approximately 1 Torr. Furthermore, it was expected that the VWP was repeatedly produced in the same position by scanning the opposite metal plate, as expected from the standing wave structure of the microwave fields in the axial direction.

In this study, we experimentally demonstrated the production of VWP excited by 2.45 GHz microwaves at an argon gas pressure of about 0.1 ~ 1 Torr and an incident microwave power of 500 W. The numerical field analysis using the 2-D FDTD method has been carried out to investigate the electric field distribution radiated from the microwave launcher. These results fairly agreed well with the experimental results. In the absence of plasma, a certain cavity mode was formed inside the chamber, depending on the axial position of the terminating metal plate. As expected, the plasma was repeatedly produced in the region of high electric field intensity by scanning the opposite metal plate.

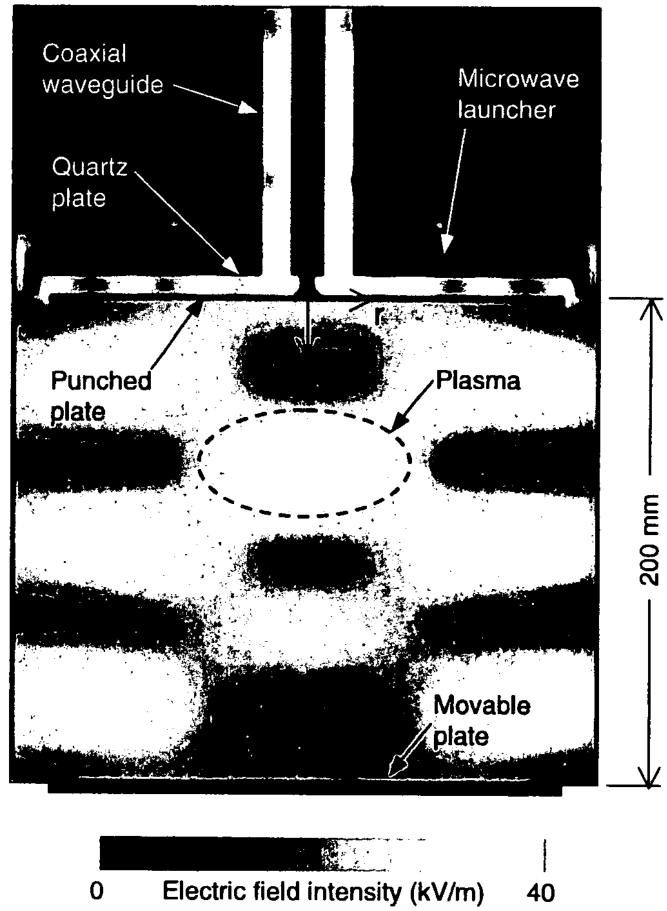

Fig. 5. 2-D plot of spatial distribution of electric filed intensity calculated assuming that microwave power is 500 W without plasma discharge in discharge chamber.

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